Isospin effect on pre-scission $\gamma$ emission

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Abstract

The influence of isospin on pre-scission giant dipole resonance (GDR) $\gamma$ decay for nuclei $^{194}\text{Pb}$, $^{200}\text{Pb}$, $^{206}\text{Pb}$ and $^{200}\text{Os}$ is explored via a Langevin equation coupled with a statistical model. It is demonstrated that with increasing the isospin of these fissioning nuclei the sensitivity of the emitted $\gamma$ multiplicity to the nuclear viscosity coefficient is decreased significantly. For $^{200}\text{Os}$ nucleus, this $\gamma$-ray emission is no longer sensitive to the magnitude of the viscosity coefficient. In addition, isospin effect on the $\gamma$ rays as a probe of nuclear dissipation is reduced with increasing angular momentum. These results suggest that to obtain a more accurate information of the viscosity coefficient by the measurement of pre-scission GDR $\gamma$-ray multiplicity it had better choose those compound systems with small isospin and low spin.

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1. Introduction

The nature and magnitude of nuclear dissipation have been the subject of great experimental and theoretical interests [1–3]. Due to dissipation, fission is delayed and this results in the enhanced emission of giant dipole resonance (GDR) $\gamma$ rays and light particles in the fission process [4–9]. Therefore they are considered to be important indicators for nuclear dissipation. Theoretical analysis of experimental observables based on diffusion models [10–21] mainly focuses on light particle emission, evaporation residue cross sections and the kinetic energy distribution of fission fragments. In contrast, although Fröbrich and Gontchar found that $\gamma$-ray multiplicity is a more sensitive probe of nuclear viscosity coefficient than light particles [22], till date theoretical studies involving $\gamma$ decay in the dissipative fission are still very rare. On the experimental side of $\gamma$ emission, now total energy spectra of $\gamma$ multiplicity in the fission process, which is a sum of GDR $\gamma$ decay from fission fragments and pre-scission compound system, can be measured, while the extraction of pre-scission $\gamma$-spectra and multiplicities resorts to a statistical model analysis [6–8]. Hence it still lacks direct (without a statistical model analysis in between) experimental information about the pre-scission $\gamma$ multiplicity. Despite these difficulties, an agreement between pre-scission GDR $\gamma$ multiplicity data for the $^{224}\text{Th}$ system and Langevin calculations was obtained by Fröbrich and Gontchar [10].

A recent work [23] showed that isospin affects the particle emission and that with increasing the isospin of the system the emitted charged particles are not a good observable of the viscosity coefficient. The present work devotes to investigating isospin effects on the pre-scission GDR $\gamma$-ray emission as a probe of nuclear dissipation by means of Langevin equations.

2. Theoretical model

A combined dynamical Langevin equation and a statistical model (CDSM) is employed to study $\gamma$-ray evaporation in the fission process. Since the present model is the same as that of Refs. [10,24], so here a brief introduction to the model is given. The dynamical part of the CDSM model is described by the Langevin equation which is driven by the free energy $F$. In the Fermi gas model, $F$ is related to the level density parameter
GDR emission is from Ref. [29], which is the same as that used in Refs. [6,7]. Note that some γ-ray emission widths. For the γ-emission, the strength function for γ-emission to the viscosity coefficient (β) at excitation energy $E^* = 100$ MeV and three critical angular momenta $\ell_c = 30, 50$ and 70 h. The lines are guides to the eyes.

Fig. 1 shows the change of pre-scission γ-ray multiplicity ($E_\gamma \leq 30$ MeV) of systems $^{194}$Pb, $^{208}$Pb and $^{209}$Pb as a function of viscosity coefficient (β) at excitation energy $E^* = 100$ MeV and three critical angular momenta $\ell_c = 30, 50$ and 70 h. The lines are guides to the eyes.

respectively, are used for the present study. In this work, to accumulate sufficient statistics $10^7$ Langevin trajectories are simulated though such doing costs much CPU time. For each trajectory simulating the fission motion an angular momentum $L = h\ell$ is sampled from the spin distribution [10]

$$\frac{d\sigma(\ell)}{d\ell} = \frac{2\pi}{k^2} \frac{2\ell + 1}{1 + \exp[(\ell - \ell_c)/\delta\ell]}$$

(6)

describing the fusion process. The parameters $\ell_c$ and $\delta\ell$ are the critical angular momentum for fusion and diffuseness, respectively. The final results are weighted over all relevant waves, i.e., the spin distribution is used as the angular momentum weight function. Additionally, to better study the sensitivity of pre-scission γ emission to the viscosity coefficient (β), in the calculations β is respectively chosen as 3, 5, 7, 10, 15 and 20 × $10^{21}$ s$^{-1}$ throughout the fission process.

3. Results and discussions

In order to exploit how isospin affects γ-ray emission, four fissioning systems, namely $^{194}$Pb, $^{200}$Pb, $^{206}$Pb and $^{209}$Os, whose isospin values (N/Z) are 1.365, 1.439, 1.512 and 1.632, respectively, are used for the present study. In this work, to accumulate sufficient statistics $10^7$ Langevin trajectories are simulated though such doing costs much CPU time. For each trajectory simulating the fission motion an angular momentum $L = h\ell$ is sampled from the spin distribution [10]

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Fig. 1 shows the change of pre-scission γ multiplicity ($\gamma_{\text{pre}}$) emitted from nuclei $^{194}$Pb, $^{200}$Pb and $^{209}$Pb with nuclear viscosity coefficient at excitation energy of 100 MeV and three critical angular momenta $\ell_c = 30, 50$ and 70 h. The lines are guides to the eyes.

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Fig. 1 shows the change of pre-scission γ multiplicity ($\gamma_{\text{pre}}$) emitted from nuclei $^{194}$Pb, $^{200}$Pb and $^{209}$Pb with nuclear viscosity coefficient at excitation energy of 100 MeV and three critical angular momenta $\ell_c$. Note that at present range of γ-ray energy, namely $E_\gamma \leq 30$ MeV, all of the $\gamma_{\text{pre}}$ have been included. As expected, $\gamma_{\text{pre}}$ rises with β for three Pb isotopes in spite of their isospin difference. It is due to the friction effect, which leads to a decrease of fission probability and a longer
In other words, it is almost unchanged with increasing $\beta$. At $E^* = 100$ MeV and $\ell_c = 50h$, the change of $\gamma_{\text{pre}}$ of 200Pb is over 0.025 as $\beta$ increases from $3 \times 10^{21}$ s$^{-1}$ to $20 \times 10^{21}$ s$^{-1}$. In contrast, the change of $\gamma_{\text{pre}}$ of 200Os is less than 0.005, 50 times smaller than the case of 200Pb. At other two angular momenta $\ell_c = 30h$ and 70h, a similar picture is found. It should be pointed out that almost no dependence of $\gamma$ decay of 200Os on the friction strength cannot be totally ascribed to a fall of fission barrier with angular momentum though it plays a role. This is because even at angular momentum of 70h the fission barrier of 200Os has 7.5 MeV, a rather large value. It means that the high isospin of 200Os is responsible for the behavior of the insensitivity of $\gamma$ decay with friction strength. Thus the calculation for the 200Os nucleus demonstrates that for such a system with even higher isospin the pre-scission $\gamma$ multiplicity is not a good observable for nuclear dissipation. Shown in the right column of Fig. 2 is the result at a larger excitation energy $E^* = 150$ MeV. One can easily see the increment of excitation energy does not alter the sensitivity of $\gamma_{\text{pre}}$ to $\beta$ for this high-isospin 200Os nucleus.

Since in the deexcitation process of compound nuclei, fission competes with other decay channels and it has a strong dependence on the spin of the fissioning system. In addition, different experiments can produce the same compound nuclei but with different spins. So here a detailed computation of the emission of the $\gamma$ rays for three Pb systems at different angular momenta is performed. Fig. 1 exhibits the calculated $\gamma$ multiplicity at three critical angular momenta. Note that shell effects are washed out at present excitation energy of 100 MeV. As can be seen, $\gamma$ emission has a dependence on the angular momentum and it is reduced at a higher spin. This dependence comes from two aspects. Firstly, high angular momentum lowers the fission barrier, which favors fission and correspondingly suppresses the decay of other channels. Of course, these suppressed decay channels include GDR $\gamma$ decay. The second aspect is because of influence of light particle emission on the $\gamma$ decay. It has been found that with increasing angular momentum light particle multiplicity decreases [10,19]. The above two results reason in a dependence of $\gamma$ emission on the angular momentum. From Fig. 1 one can see another important effect arising from angular momentum, namely, it affects the relationship between isospin and the sensitivity of $\gamma$-ray multiplicity to viscosity coefficient. It is clear that the gaps of three lines in Fig. 1 due to isospin difference becomes narrower at large $\ell_c$. Specifically speaking, at $\beta = 7/20 \times 10^{21}$ s$^{-1}$ and $\ell_c = 30h$ the differences between 194Pb and 200Pb as well as between 200Pb and 206Pb are 0.0201/0.0329 and 0.0160/0.0169, respectively. While at $\ell_c = 50h$ they become 0.0050/0.0088 and 0.0060/0.0071. As $\ell_c$ further rises 70h, the corresponding differences are decreased down to 0.0028/0.0045 and 0.0018/0.0026. These quantitative numerical values clearly indicate that isospin effects on pre-scission $\gamma$ multiplicity as a probe of nuclear viscosity coefficient are significantly decreased with increasing angular momentum. Although $\gamma_{\text{pre}}$ at $\ell_c = 70h$ is smaller than that at $\ell_c = 30h$ and 50h, isospin effect on $\gamma_{\text{pre}}$ is still evident. It is due to the influence of competing light particle channels and their isospin dependence. Displayed in Fig. 3 are the emitted saddle-to-scission time. Both factors enhance the $\gamma$ emission. In the following we take the results at $\ell_c = 30h$ as a demonstrated example. Two evident features are noticed from this figure. First, the symbol $\square$ is always above $\bigcirc$, and the latter is above $\triangle$. That is to say, 194Pb emits more $\gamma$ rays than the case of 200Pb and 206Pb, meaning that the $\gamma$ multiplicity increases with decreasing the isospin of the system. The main reason that $\gamma$ emission depends on the isospin stems from the dependence of light particle emission on the isospin and the emission competition between different decay channels such as light particles and $\gamma$ rays. Consequently, $\gamma$ emission also depends on the isospin. Moreover, for a system with a high isospin neutron emission is significantly enhanced [23], which is unfavorable to $\gamma$-ray emission. As a result, $\gamma_{\text{pre}}$ decreases with isospin. Another feature is that the change of $\gamma_{\text{pre}}$ with $\beta$ has a large difference for three Pb nuclei. Generally speaking, the changed magnitudes of $\gamma$ multiplicity at different viscosity coefficients become smaller with increasing isospin. For instance, when $\beta$ rises from $3 \times 10^{21}$ s$^{-1}$ to $20 \times 10^{21}$ s$^{-1}$, for 194Pb the changed amount of $\gamma_{\text{pre}}$ is 4.73 $\times$ 10$^{-2}$, which is larger than that of 206Pb, whose $\gamma_{\text{pre}}$ changes 1.96 $\times$ 10$^{-2}$. This comparison indicates that the sensitivity of the emitted $\gamma$ multiplicity to $\beta$ is lowered at a large isospin.

To further explore isospin effect on the GDR $\gamma$ emission as an observable of nuclear dissipation. We depict in Fig. 2 the calculated results for a higher isospin system 200Os. As a reference, the data of 200Pb are also plotted. Obviously, the $\gamma$ ray emitted from 200Os is insensitive to the viscosity coefficient.
neutrons, protons and α particles as functions of isospin and viscosity coefficient at $\ell_c = 70\hbar$. As is seen, $N_{\text{pre}}$ is an increasing function of the isospin of three Pb nuclei, $P_{\text{pre}}$ and $\alpha_{\text{pre}}$ are a decreasing function of the isospin. It is obviously related to the systematics of the neutron number of fissioning sources. These types of behavior can be explained in terms of the change of the particle separating energy for fissioning sources with different isospins. Furthermore, the multiplicity of protons and α particles of $^{206}\text{Pb}$ is almost independent of $\beta$, which is different from the case of low-isospin $^{194}\text{Pb}$. This is a consequence of a stronger neutron emission of $^{206}\text{Pb}$ than $^{194}\text{Pb}$ since Fig. 3 reveals that $N_{\text{pre}}$ of $^{206}\text{Pb}$ is over 1.5 times that of $^{194}\text{Pb}$. Enhanced neutron emission lowers not only charged particle decay but also other decay channels, such as $\gamma$ decay. The variation of $\gamma_{\text{pre}}$ with isospin illustrated in Fig. 1 also show this point.

It should be mentioned that we also carry out the same calculations at other excitation energies and find that the conclusions are similar and hence not repeated here. Also, considering that the experimental data in Refs. [7,8] are discussed in terms of ratios (it refers to the ratio of emitted GDR $\gamma$ multiplicity before scission to that from post-scission [7]), and this method of ratio has proven to be a very sensitive tool to reveal dissipation effects [7,8], thus extending the present model to include post-scission emission is interesting.

4. Summary and conclusions

In conclusion, using the Langevin equation containing various particle emission we explore the isospin effect on the pre-scission GDR $\gamma$-ray emission. Calculations show that such an effect is rather strong so that for a high-isospin fissioning nucleus $^{200}\text{Os}$, the $\gamma$-ray emission is no longer sensitive to nuclear viscosity coefficient. Moreover, it is found that this isospin effect becomes weak at high angular momentum. These results suggest that in order to get an accurate information of viscosity coefficient by measuring pre-scission $\gamma$ multiplicity it had better choose those compound systems with small isospin and low spin.

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References